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A MEMS resonator as a power receiver for inductively powered implantable sensors

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Abstract

Power transfer by inductive coupling between two L-C resonant tank circuits is commonly used as a powering method for implantable sensor devices. However, mechanical resonators offer a possibility of improved efficiency due to their higher Q. A quartz tuning fork crystal was investigated for this purpose by mounting miniature magnets on its extensions. The capability of electrical power reception from an alternating magnetic field was investigated, along with the possibility of a fully mechanical sensor with acoustic feedback.

Keywords: Wireless power transfer; Tuning fork; MEMS resonator; Magnetic Coupling; Implantable Sensor

1. Introduction

In the rapidly developing field of implantable sensors, there is a constant need for prolonged operation time along with shrinkage of the device dimensions. The use of batteries as a power source remains a major limitation in these aspects, leading to investigation of alternative methods such as energy harvesting and wireless power transmission. Inductive wireless power transmission (IWPT) utilizes alternating magnetic fields to transfer energy between two resonant structures. Typically these are a pair of L-C resonators forming a loosely coupled transformer. Previous work[1] has shown that for a weakly coupled system of L-C resonators, energy transfer efficiency can be described by an equation

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$$\eta = \frac{P2}{P1} = \frac{k^2 Q_1 Q_2}{1 + k^2 Q_1 Q_2} \tag{1}$$

Where Q_1, Q_2 are quality factors of the resonators, and k is the inductive coupling coefficient. Practical resonators typically demonstrate Q values of 100-1000 using high quality litz wire coils, 10-100 with chip SMT inductors and less than 10 for on-chip integrated coils[2]. Scaling to chip-size dimensions also tends to increase the minimal attainable resonant frequency towards 100's of Mhz where efficient RF generation is difficult and tissue absorption losses are high.

On the other hand, MEMS resonators have demonstrated Q exceeding 10^6 [3]. If equipped with a suitable means of coupling with an alternating magnetic field and providing electrical output, a mechanical resonator becomes highly attractive as a replacement for its electrical counterpart, especially at the receiver side where improvement in Q is most significant and small dimensions are required. As an added benefit, mechanical resonators also allow much lower minimal resonant frequencies for the same device dimensions. The resulting concept becomes effectively a variant of energy harvesting where energy is supplied externally in form of alternating magnetic field. While energy harvesting is recently a very active topic, attempts to utilize mechanical resonators for wireless power transfer remain relatively scarce. A notable example is [4] based on 80x6x0.6mm magnetostrictive-piezoelectric resonator, while [5] uses a simple spring-cantilever system with rare-earth magnets.

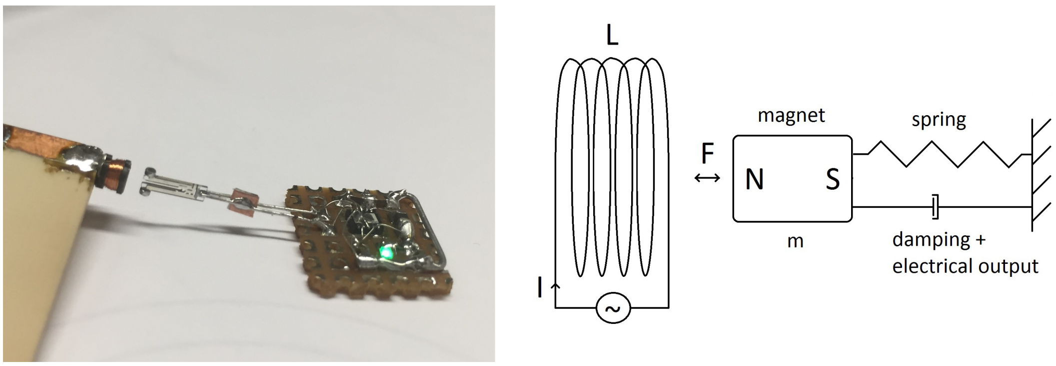

Figure 1. Left: Piezoelectric tuning fork topped with neodymium magnets, powering a LED with help of LT3588 energy harvesting IC. Right: basic principle of energy transfer to a mechanical resonator using alternating magnetic field.

The goal of this work is to investigate the feasibility of using small-scale micromachined MEMS devices for the purpose of wireless power reception. A quartz tuning fork oscillator crystal comes as a very useful experimental tool. It is a resonator with a high degree of symmetry providing high Q even without vacuum encapsulation, and already provides piezoelectric output. Magnetic coupling may then be achieved using a pair of magnets as additional "proof masses" onto each of the fork cantilever, with the same poles facing each other.

An idealized model of a MEMS resonator (represented by a magnet with mass m on a spring) driven by a AC-current carrying coil is shown of fig.1, right. The magnetic field gradient results in a force F acting upon the resonator, which can be approximated with linear relationship with current for small oscillation amplitudes

$$F = k_m I \sin \omega t \tag{2}$$

While it is clear that increase in Q benefits the power transfer efficiency, the question remains what comprises the magnetic coupling constant k in a coil-magnet system? How does it relate to the above k_m and possibly other parameters? Integrating the force (2) and dividing by mass m yields velocity v of a free, non-resonating mass. At resonance, the velocity is amplified by factor Q_2, and is also in phase with force allowing easy calculation of output power by multiplying their RMS values:

$$P_2 = \frac{{k_m}^2 I^2 Q_2}{2\omega m} \tag{3}$$

By putting this into (1), along with $Q_1 = \frac{\omega L}{R}$ and $P_1 \approx \frac{I^2}{{Q_1}^2} R$ the new coupling constant k' is obtained:

$$k' = \frac{k_m}{\sqrt{2mL}} \tag{4}$$

The coupling now depends on mass and inductance, as well as much less understood parameter k_m. As seen in[5], it may depend on whether the coupling is force or torque based, and possibly depend much more strongly on coil dimensions than electrical k, which remains to be tested by experiments.

2. Materials and Methods

2.1. Resonator Construction and Testing

32.768kHz watch crystals in 3x8mm cans (IDQ frequency LFXTAL002996, farnell 2449410) were decapsulated by repetitively squeezing the epoxy seal at the bottom with pliers while rotating the package, in order to cause the resin to crack and break up from fatigue. It is advisable to solder the pins to a small piece of PCB to prevent breaking the bond with the tuning fork as well as to reduce detrimental heating of the magnets by later soldering. Two 0.5x1mm disc shaped N35 grade NdFeB magnets are placed horizontally (same poles facing up) on a ferromagnetic surface and a drop of Loctite 3526 UV-sensitive adhesive is placed on them using a glass pipette. The tuning fork is then brought into contact and adjusted under microscope for a symmetrical alignment with the magnet. The glue is then cured with an UV LED, after which the fork is rotated and the process repeated for another magnet. The resulting device is shown on fig. 1, left.

The basic tests were performed using a 1.2mH SMT inductor (pictured on the left of fig. 1, left), which is driven directly by the function generator. A higher power driver using a complementary power MOSFET half-bridge was constructed as well, driving a 100-turn, 320mm wide coil in a series resonant configuration.

2.2. Direct Strain Sensing Using a Third Magnet as a Modulator

Most miniature sensors used in implantable devices are already MEMS-based. If only mechanical energy is required for sensor operation, an exciting possibility arises: The received mechanical energy could be used directly, without performing a mechanical-to-electrical conversion and eliminating unnecessary complexity and energy losses. For example, a tuning fork could be used directly as a gas pressure sensor since its Q and resonant frequency are directly affected by pressure. Alternatively, the resonant frequency may be modulated using a third, movable magnet – useful for, for example, strain, pressure or acceleration sensors. Acoustic output radiated by the tuning fork could in this case serve as backward communication channel, by being picked up by extracorporeal microphone and allowing precise determination of resonant frequency. Whether this is possible depends mainly on the intensity of generated sound.

An experiment was devised to test this idea as follows. A magnet-equipped tuning fork was mounted in a fixture together with an excitation coil, as visible in fig.2, left. The modulation magnet was actuated using a micromanipulator, while the piezoelectric output of the tuning fork was full wave rectified and monitored with multi-meter. The input frequency is adjusted for maximum output voltage, after which the modulation magnet is moved for a fixed distance (25.4 micrometers) away from the tuning fork tip. This is repeated up to distance of about 200 micrometers after which the measurement becomes unreliable.

3. Results and Discussion

The produced devices typically resonated between 12 and 16 kHz. The quality factor measurements yielded 70000, 8400 and 1700 for the encapsulated, decapsulated, and magnet-loaded tuning fork respectively, suggesting a possible benefit from vacuum encapsulation. As the drive power was increased, tuning forks showed a tendency to self-destruct unexpectedly due to mechanical overload, obstructing the quantification of the maximum power output of a particular crystal. Largest measured short circuit current and open circuit voltage imminently before failure were 30.6 μA and 39.24 V, suggesting an output power limit of about 300 μW. Such a high output impedance mandates use of a step-down converter for most typical loads, significantly increasing size and complexity. Fig.1 shows a LED being driven using LTC3588 energy harvesting IC. Maximal output attainable this way was 2.5 V at 60 μA (150 μW). The strain sensing test showed a nearly linear frequency-displacement for displacements smaller than 150 μm, with sensitivity of 0.0326 Hz/μm. Surprisingly, resonating tuning forks were clearly audible even at 16kHz and could be easily recorded by a smartphone, suggesting a possibility of using sound as a method for Q and frequency measurement. Using the large 320mm coil, 16W input power was required for 45μW (0.00028% efficiency) output with the receiver device at the centre, in plane with the coil. A 3x20mm ferrite rod needed to be placed 0.5mm from the magnets to increase local flux gradient. In comparison, an electrical resonator with similar volume (9 mm^3) demonstrated efficiency of 0.024% at 4Mhz with a Royer oscillator driver, the same transmitting coil dimensions and the location within it. The conclusion is that even though the Q is increased, the coupling constant k′ remains extremely small compared to the electrical counterpart, and requires further investigation.

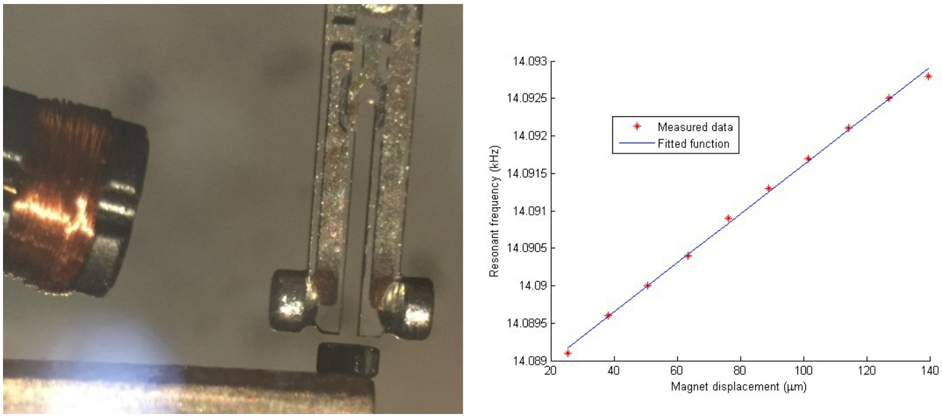

Figure 2. Left: Strain sensor test setup. Right: Resonant frequency of the tuning fork as a function of displacement of the movable modulating magnet.

4. Conclusion and Future Directions

A quartz tuning fork based wireless power receiver was fabricated and proven capable of useful power output. Furthermore, it was used to demonstrate a basic principle for a fully mechanical-energy based wireless sensor, with acoustic signal as feedback. The main issue remaining to be solved is optimization of coupling in very low magnetic field gradients, and testing with various transmitting coil sizes is required to make useful comparisons with electrical resonators. Further work includes designing micromachined resonators in silicon, further reducing their size and developing lithographic methods for patterning of magnetic material to replace discrete magents.

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